

Open Research Online

The Open University's repository of research publications
and other research outputs

L-VRAP-a lunar volatile resources analysis package for lunar exploration

Journal Item

How to cite:

Wright, I. P.; Sheridan, S.; Morse, A. D.; Barber, S. J.; Merrifield, J. A.; Waugh, L. J.; Howe, C. J.; Gibson, E. K. and Pillinger, C. T. (2012). L-VRAP-a lunar volatile resources analysis package for lunar exploration. *Planetary and Space Science*, 74(1) pp. 254–263.

For guidance on citations see [FAQs](#).

© 2012 Elsevier Ltd

Version: Accepted Manuscript

Link(s) to article on publisher's website:
<http://dx.doi.org/doi:10.1016/j.pss.2012.08.014>

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's data [policy](#) on reuse of materials please consult the policies page.

oro.open.ac.uk

Article title: L-VRAP - a Lunar Volatile Resources Analysis Package for Lunar Exploration

Reference: PSS3389

Journal title: Planetary and Space Science

Corresponding author: Dr. S. Sheridan

First author: Dr. I.P. Wright

Online publication complete: 10-OCT-2012

DOI information: 10.1016/j.pss.2012.08.014

L-VRAP - a Lunar Volatile Resources Analysis Package for Lunar Exploration

I.P.Wright¹, S.Sheridan¹, A.D.Morse¹, S.J.Barber¹, J.A.Merrifield², L.J.Waugh³,
C.J.Howe⁴, E.K.Gibson⁵ and C.T.Pillinger¹

¹ Planetary and Space Sciences, Open University, Milton Keynes, MK7 6AA, UK

² Fluid Gravity Engineering, 1 West Street, Emsworth, PO10 7DX, UK

³ EADS Astrium Ltd., Gunnels Wood Rd., Stevenage SG1 2AS, UK

⁴ RAL Space, Didcot, Oxfordshire, OX11 0QX, UK

⁵ Astromaterials Research Office, NASA-JSC, Houston, TX 77058, USA

Abstract

The Lunar Volatile Resources Analysis Package (L-VRAP) has been conceived to deliver some of the objectives of the proposed Lunar Lander mission currently being studied by the European Space Agency. The purpose of the mission is to demonstrate and develop capability; the impetus is very much driven by a desire to lay the foundations for future human exploration of the Moon. Thus, L-VRAP has design goals that consider lunar volatiles from the perspective of both their innate scientific interest and also their potential for in situ utilisation as a resource. The device is a dual mass spectrometer system and is capable of meeting the requirements of the mission with respect to detection, quantification and characterisation of volatiles. Through the use of appropriate sampling techniques, volatiles from either the regolith or atmosphere (exosphere) can be analysed. Furthermore, since L-VRAP has the capacity to determine isotopic compositions, it should be possible for the instrument to determine the sources of the volatiles that are found on the Moon (be they lunar per se, extra-lunar, or contaminants imparted by the mission itself).

1. Introduction

To date, just 2.9% of the lunar surface (5.8% of the front side) has been subjected directly to human scrutiny, all of the activity having taken place forty years ago. Now, a program of activities has been defined and proposed by the ESA Directorate of Human Spaceflight and Operations in preparation for future human exploration of the Moon (Carpenter et al., 2012). Herein we consider how one of the key issues for such exploration, the availability (or otherwise) of volatiles that would be useful in a resource context, could be addressed by robotic means through a precursor mission(s).

ESA has identified the Lunar Lander mission as the first strategic step in the development of capabilities for participation in the future international lunar exploration effort. The primary objective of the first European Lunar Lander mission is to demonstrate the ability to deliver a payload, via autonomous precise soft landing with hazard avoidance, safely and accurately to

the Moon's surface. With a launch date planned no later than 2018 (or early 2019), which will provide an opportunity to perform investigations on the Moon that are essential to the success of lunar exploration and that must be carried out in advance of an extended human presence. Such investigations will address the survival of humans in the lunar environment and ensure the sustainability of lunar exploration.

One candidate investigation is the characterisation of the nature and distribution of volatiles at or near a polar landing site. Volatiles are a potential resource to be utilised in future missions and in order for volatiles to be exploited (In Situ Resource Utilisation, ISRU) they need to be found, extracted, identified, quantified, their origin demonstrated, etc. Hence, there is a need for a sampling/analysis package of some sort; the device we have considered (LVRAP) is designed to address these requirements.

2. Science Drivers

The case for the scientific investigation of volatiles at the lunar surface is given in a companion paper (Pillinger, et al., 2012). The very term “volatile” is, of course, a little bit loose but, in fact, the requirements for the ESA Lunar Lander are reasonably well defined (and are discussed below). The renaissance of water on the Moon as a serious possibility provides a strong imperative in the thinking of instrument designers and scientists alike. Here we should recall the enormous amount of work that was dedicated to the analysis of returned lunar samples from Apollo (and Luna) missions, including seminal papers on the investigation of hydrogen/water (e.g. Epstein and Taylor, 1970; Friedman et al., 1970; Gibson and Johnson, 1971). We should note that hydrogen/water has, for a long time, been central to thoughts involving resource utilisation on the Moon (e.g. Gibson et al., 1988).

In more recent times it was not until the mid-1990s that an opportunity to search for ice deposits arose using a radar instrument on NASA's Clementine spacecraft (Nozette et al., 1996). Although this interpretation has been questioned because the Arecibo radio telescope was unable to obtain corroborating radar data (Stacey et al., 1997; Simpson and Tyler, 1999), small isolated lenses of ice within the regolith are not ruled out by these observations. In support of Clementine's conclusion, a similar experiment had already been successfully performed for Mercury, using an Earth-bound transmitter and radar receivers. Mercury is a planet much closer to the Sun and with equatorial surface temperatures in the region of 430°C, and yet it shows the possible existence of polar ice, most likely a consequence of its rotational characteristics (Campbell et al., 2006). Further orbiting radar studies of the lunar surface, and in particular investigation related to permanently shadowed areas, including polar craters, have been conducted with the Indian Chandrayaan-1 mission. The findings of the Moon Mineralogy Mapper (M^3) on-board the spacecraft have been interpreted as being due to the presence of OH/H₂O in the top most millimetres of the lunar regolith (Pieters et al., 2009).

The NASA spacecraft, Lunar Prospector, which was equipped with a gamma ray/neutron spectrometer, found that not only were there high hydrogen concentrations within a couple of degrees of latitude of the lunar poles (most noticeable in the south polar Aitken basin and the crater Shackleton), but that hydrogen abundances increased threefold when the areas of permanent shadow were targeted (e.g. Feldman et al., 2001). An interpretation of gamma ray data is that high H abundance is equivalent to a high water/ice content. However, high concentrations of solar wind hydrogen could also be an equally plausible interpretation of some of the data (Schmitt et al., 2000).

The most recent information concerning the lunar volatile inventory derives from the joint LRO/LCROSS mission (Lunar Reconnaissance Orbiter/Lunar Crater Observation and

Sensing Satellite). During its approach to the Moon, instruments (on LRO) recorded the presence of hydrogen at the lunar surface. Indeed, it appeared that water could be present at levels of between 0.5 and 4.0% by weight, depending on the thickness of any overlying dry regolith (dust) layer. Some interpretations suggest that this layer could be up to 40 cm thick. On the basis of these results, the Cabeus crater (about 100 km from the lunar south pole) was selected for the LCROSS part of the mission (Mitrofanov et al., 2010). In this, the spent upper stage of the Atlas V Centaur launch vehicle impacted into Cabeus, whilst instruments on board LCROSS, which followed behind five minutes later, monitored both the high angle impact plume and the lateral ejection of debris. LRO was able to view the impact site during repeated overflights of Cabeus (after the contact) to show a 25-30 metre crater had been produced (Colaprete et al., 2010). Since the impact of the Centaur took place at around 2.5 km s^{-1} , the temperatures initially associated with the impact event (ca. 1000 K) were sufficient to release any volatiles present. The ultimate detection of volatiles was taken to imply that they had been released from permanently shaded regions of Cabeus. But, measurements of surface temperatures using a radiometer (Paige et al., 2010; Hayne et al., 2010) showed that cryogenic circumstances exist well beyond the extent of the shaded areas and into the sunlit parts of the polar surface. Although the lowest temperatures obtained (38 K) were for the dark locations in craters (i.e. like the impact site) it appears that large areas below 80° S would be sufficiently cold to allow cryogenic trapping of the volatile species of interest to L-VRAP. This has important implications since it means that lunar volatiles can be found outside permanently shaded regions (e.g. Kerr, 2010) and could be investigated by a lander using solar powered systems and batteries (a requirement of the ESA lunar lander mission), as opposed to radioactive devices.

3 Mission considerations

L-VRAP is a candidate payload element for the ESA Lunar Lander mission and offers the opportunity to take key steps in the resource, scientific and technological investigation of the Moon. Whereas data from previous orbiters and samples returned by humans, robots and the hand of nature (i.e. samples ejected as meteorites) have provided measurements concerning volatiles on the Moon, L-VRAP can contribute significant new and improved data in a number of respects:

- Information concerning Polar Regions, where it is believed volatiles may be concentrated due to cryogenic trapping
- Measurement of samples with minimal and constrained contamination (see section 3.1)

The requirements for L-VRAP include a number of "proof of concept" studies aimed at ISRU. This raises an interesting issue since the ability to utilise something necessarily implies that it has to be extracted. In this sense, an instrument that could measure volatiles remotely, or without extracting them into a container of some sort, would not fit the requirements. So, for instance, the instrument concept known as DORN, the Detection of Outgassing Radon (see Meslin et al. 2011), which uses the emanation of ^{222}Rn as a proxy for water content and movement in the regolith, whilst relevant for scientific investigations, is not appropriate for demonstrating resource utilisation. We consider, however, that even demonstration of just one extraction is not completely straightforward. Extraction methods tailored for subsequent scientific investigations are not necessarily feasible for ISRU purposes. Scientific extraction methods might include:

- Thermal desorption of samples received from a sampling system, a number of heating techniques being available

- Use of chemical reactions
- Thermal desorption by heating in situ, e.g. by an instrumented mole, or laser desorption
- Use of natural lunar temperature cycles to liberate volatiles
- Dumping heat from the lander platform to the instrument package itself

Of these, several are unlikely to be feasible from a practical consideration (e.g. energy usage) for ISRU purposes. Thus, the L-VRAP approach needs to be something that keeps one eye on reality.

Samples analysed by L-VRAP should, under ideal circumstances, be characterised by any other instruments present on the lander (including cameras with filters that would allow observations in different wavelength bands). From a resources perspective, the exact location of the samples is likely to be a high priority since this will establish the availability of volatiles; the actual nature of the samples is probably of more importance from a scientific standpoint.

The requirements for L-VRAP as interpreted herein, are shown in table 1. RQ1-RQ5 are considered to be high priority requirements and RQ6-RQ7 are medium priority requirements.

The requirements for RQ1-4 can be summarised as follows; Extract volatiles, Identify extracted volatiles, Quantify extracted volatiles and determine the chemical and isotopic abundance of volatiles in source regolith. Whilst subsurface sampling is a desirable requirement for the L-VRAP study, samples collected from close to lander platform may, by default, be subsurface if the force of the exhaust plume strips the landing site of “loose” material as was apparent at the landing sites of Apollo and Luna missions. Examination of pristine surface materials may require a Mobile Payload Element (MPE); indeed, one capable of travelling several hundred metres away from the landing site. In principle this might involve an instrumented rover that can travel to, and perform analyses in, localities outside the area contaminated during landing; more realistically it is likely to be a sample-fetching device that can collect uncontaminated samples and bring them back for analysis by the Lander’s onboard instruments such as L-VRAP. Alternatively it might be that the analysis of sub-surface samples taken in the vicinity of the lander is technically more feasible than having a mobile payload element with a sufficient range. Sub-surface sampling at a level of, say, 0-10 cm (or, more usefully, 0-40 cm) within range of the lander would be capable of complying with requirements RQ1-RQ4 above.

RQ5 is concerned with obtaining ground truth for orbital observations to achieve the required surface data and to avoid/minimise contamination effects from the landing event. Sample collection systems need to collect an undisturbed top ~1 mm sample at a suitable distance from the landing site or at a location protected by local topography (sheltered regolith behind a rock for instance). Observations made concerning Surveyor III, however, suggest effects of the landing spacecraft engines’ exhausts may not be unidirectional. It is considered unlikely that requirement RQ5 can be met without a mobile payload element that has a range exceeding the extent of the exhaust contamination. It should be noted that data interpretations from LRO/LCROSS suggest that the information required is for a measure of H₂O/OH abundance at a depth immediately below any shielding regolith and not from the first 1 mm.

RQ6 addresses neutrals in the lunar exosphere. Given the tenuous nature of the exosphere the data are very important as they will allow (i) determination of the natural condensation/release parameters for lunar volatiles (including exhaust contaminants) and (ii)

a long term assessment of the affects on the delicate lunar environment by increased lander (both robotic and human) mission activities. The lunar exosphere in the vicinity of the landing spacecraft will be dependent on many parameters e.g. time of day (night), temperature, proximity of sampling, out gassing of the lander, sampling method, etc.

Measurements of the lunar atmosphere will provide information on the processes occurring that lead to volatile concentration at the poles. Meeting the requirements of RQ6 needs an instrument with the highest possible sensitivity. L-VRAP therefore needs to be capable of monitoring volatiles at number densities $<1 \text{ molecule cm}^{-3}$ for CH_4 , H_2O , CO_2 , NH_3 . The only effective approach here is to include an atmospheric collection/concentration feature as part of L-VRAP.

3.1 The consideration of contamination

The effect of contamination is something that needs to be evaluated within the scope of the L-VRAP design (since, in part, it may be an essential aspect of a campaign to characterise the contamination imparted to the Moon by its very exploration). What is needed (prior to flight) is some kind of assessment of the likely nature and extent of contamination and alteration of the lunar surface resulting from the action of the Lunar Lander's motors during descent. Although we already have evidence from the Apollo missions it should be noted that the proposed ESA Lunar Lander descends more abruptly in the final near-surface stages, which is where contamination and alteration effects are most prevalent and hence these effects will be reduced. Nevertheless it is likely that the Lander's robotic arm will not be able to access unaltered surficial regolith material (unless it is shielded by serendipitous local topography, e.g. rocks, which, of course, cannot be relied upon). Hence it is considered that the approach most resilient to delineating the effects of contamination comprises a combination of:

- Measuring volatiles as a function of lateral distance from Lander (to investigate decline in alteration with distance)
- Measuring volatiles as a function of depth
- Being able to recognise contamination effects in acquired data

Without proper evaluation of the potential for contamination at the lunar surface (i.e. at the landing site and environs), the goals of L-VRAP may be compromised. In order to address this we have undertaken the following:

- A preliminary characterisation of the Lunar Lander's propulsion system
- Calculation of the exhaust gas flow field
- Assessment of the surface fluxes (skin friction and heat transfer) resulting from the time varying flow field
- Calculation of in-depth flow solution resulting from rocket plume impingement (flow through a porous medium) and an assessment of the likely level of surface erosion

The nature of the challenge is illustrated in Figure 1 and is discussed in ESA Document AO/1-6620-LVRAP-TN3. Trajectory and thrust profiles were provided from ESA along with a rocket motor data pack that allowed the propulsion system to be characterised using the NASA Glenn code CEA. The plume flow field solution is analytic in nature: surface pressures were calculated from Newtonian theory using either a single point source of momentum, where the combined effect of multiple engines were treated using thrust averaging (this is the SEN, or Single Equivalent Nozzle, approach), or by superimposing the effect of multiple point sources of momentum, each of which represents one individual

engine. Viscous fluxes to the regolith were assessed using boundary layer analysis in which edge properties were derived from the equations of isentropic expansion. This approach is only valid for the pressure distribution obtained from the SEN approach. That is, heat flux and shear stress are derived from the SEN treatment. The shear stresses obtained from this analysis were used to estimate a rate of surface erosion. The rate of surface erosion was integrated over time to obtain a total erosion for specific surface locations with respect to the landing site. The time history of surface heat flux was calculated from boundary layer analysis has been used to estimate thermal conduction into the regolith and its subsequent heating (surface and in-depth). This was performed using the 1D finite difference code FABL, which is primarily used to assess the ablation of the thermal protection system of entry probes (such as that on Beagle 2, a mission to Mars that is described in Sims et al, 1999). Results from this were used as a boundary condition for a 1D time-dependent porous flow solver and from this it was possible to estimate the effect of in-depth contamination of the regolith.

An example of the modelling is given in Figure 2 for locations that would be easily accessible by the proposed robotic sample collection arm. Here the internal flow 1.2m away from the geometric axis of the lander was calculated at two locations. The location at zero degrees is close to two ATV motors whilst the location at 45 degrees is further from this source of contamination (for these calculations, the surface pressure boundary condition was taken from multi-nozzle calculations). Regolith erosion due to viscous dust entrainment (as formulated by Roberts (1963)) is shown in Figure 3 and was found to be small for the test locations studied here (~2 mm). However, we note that in reality other mechanisms for soil removal may be at play and further study is required to confirm that the erosion environment is likely to be quite as benign as this analysis suggests. In particular the effect of Diffuse Gas Erosion (DGE) and the more dramatic Diffuse Gas Explosive Erosion (DGEE), which can dominate when supersonic pulsed jets generate high pore pressure gradient forces with respect to soil weight, should be investigated. These phenomena are not adequately described by the 1D porous flow calculations performed herein since they are significantly affected by high-pressure gas diffusing radially outward from the centre of the impinging plumes.

Mindful of the above limitations we have found that significant penetration of exhaust gas into the lunar regolith during engine operation is only likely to extend down to a few centimetres at the test locations considered. This conclusion must be tempered by two additional considerations:

- The exhaust gas will continue to diffuse into the regolith after engine shutdown as well as escaping from the surface. This will lead to a deeper penetration depth.
- The 1D diffusion model here does not take account of high pressure gas which will enter the regolith closer to the centre of the lander diffusing out radially and thus leading to contamination at the test locations. That is, the 1D nature of diffusion model as applied at the test locations may not be justified.

Both these considerations will lead to the exhaust gas penetrating deeper into the regolith than indicated in the Figure 2. However, this does not necessarily mean that significant contamination will exist at these increased depths since (from our thermal response calculations) we see that, even though surface heating can be significant (~550 K at the 45 degree test location), due to the extremely low thermal conductivity of the regolith, this heat does not penetrate particularly far into the surface (less than 1 cm). This is because heat radiates away from the hot surface more quickly than it is conducted into the bulk of the

material. As such, volatiles (in particular water vapour) being advected into the surface by the porous flow should be condensed out on the cold in-depth surfaces of the regolith particles without penetrating deeper into the bulk of the regolith.

Based on the calculations performed thus far, a contamination depth of a few centimetres seems justifiable and thus, taking samples at a depth of approximately 10 cm will help to mitigate the effect of surface alteration. Notwithstanding this conclusion, more detailed modelling of the exhaust plume effects are clearly warranted.

A very important observation made by the Apollo missions was that the number of species in the lunar atmosphere (exosphere) was roughly doubled as a result of gases added by the activities associated with successive missions. The effect that future exploration will have on the lunar environment, particularly its tenuous atmosphere, is something that must be carefully monitored; investigations like L-VRAP will have an important role in such an activities.

4. L-VRAP Conceptual Description

The L-VRAP concept is a development of the MODULUS (Methods Of Determining and Understanding Light elements from Unequivocal Stable isotope compositions) philosophy that was initially developed for the ESA Rosetta mission and further refined for Beagle 2 (Wright and Pillinger, 1998; Wright et al., 2003). The MODULUS approach has been specifically tailored for a lunar polar lander set of objectives. It comprises a miniature “chemical laboratory” capable of undertaking geochemical investigations analogous to the many experiments that have been performed on returned lunar samples. For L-VRAP it incorporates the following elements:

- Collection and analysing exospheric samples.
- Transportation of regolith samples from a sampling device.
- Determining (or estimating) the mass of a regolith sample.
- Extracting volatiles from samples.
- Methods of purifying and/or separating evolved gases.
- Qualitative, quantitative and isotopic analysis of volatiles.

The L-VRAP concept as developed in response to the ESA call AO/1-6620/10/NL/GLC and described in AO/1-6620-LVRAP-TN4 is shown in schematic form in Figure 4 and a view from the CAD model is shown in Figure 5. Within the Structural and Thermal System (STS) enclosure are a Solid Inlet System (SIS), Sample Processing System (SPS), Atmospheric Analysis System (AAS) and the Magnetic Sector System (MSS), all of which are controlled by a Local Electronics System (LES) that also performs power distribution, communications and data handling functions.

4.1 Atmospheric Analysis System

The AAS is based around an ion trap mass spectrometer (see Todd et al., 2006; Wright et al. 2007; Morse et al., 2009) that is capable of measuring incident neutral volatile species in real time. A second mode of operation involves use of a cooled adsorbent material to collect and concentrate neutrals for a period of time prior to releasing them by heating into the ion trap for analysis. The ion trap has a mass range of 10 to 300 amu and with a unit mass resolution. A final possibility is that the ion trap can be used to “screen” volatiles released by the SIS by allowing small portion of released gases into the ion trap for a rapid pre-analysis of composition.

4.2 Solid Inlet System

The SIS receives a regolith sample from the Lander's sample collection mechanism i.e. the robotic arm with scoop and/or a mobile payload element with an associated mole (Richter et al. 2002). The SIS is based on the Beagle2 design with the addition of a sample imager. A piezoelectric actuator is available to aid sample transfer into the sample ovens from the sample inlet funnel under the influence of gravity. Care is needed to ensure undesired electrostatic effects during sample transfer and a charge neutralisation device may be required.

The sample is deposited into one of 24 small "ovens" mounted on a rotary carousel. The drive mechanism for this is located below the carousel in a dust-proof enclosure to minimise the effects of dust ingress on the mechanics of the drive system. The carousel can rotate to place the sample oven below one of three functional stations: a sample imaging station, an oven clean-up station and an oven docking station.

The sample imaging station, allow direct characterisation of the sample deposited into the oven by a miniature CMOS camera which provides confirmation material has been deposited into the oven and allows an estimation of sample mass.

The oven clean-up station removes dust/contaminants from the sealing surface at the top of the oven to allow a gas tight seal to be made. The presence of dust on the sealing surface would allow sample gas leakage prior to analysis.

The oven docking station is where a gas-tight seal can be made between the oven and a sample transfer pipe. The baseline method of volatile extraction used in L-VRAP is by heating the sample. Liberated volatiles are transferred into the L-VRAP instrument for characterisation and analysis.

4.3 Solid Processing System

The SPS can condition, separate and purify the incoming mixture of gases utilising a number of components distributed amongst a number of cold, ambient and hot manifold sections. The Sample Processing System is used to process volatiles physically and chemically into species suitable for isotopic analysis by the mass spectrometer. Additionally a reference gas system allows the generation and metering of gases for calibration purposes.

A schematic of the SPS and interaction with other sub-systems is shown in figure 6 and consists of a number of discrete manifold assemblies; namely the "hot", "warm", "cold-finger" and "reference". The hot manifold processes and purifies volatiles which may contain a high concentration of water vapour hence it is maintained at a "hot" temperature to prevent water vapour from condensing on the internals of the system, prior to conversion into non-condensable forms for analysis. In addition there is a cold finger, which will be used to remove (or separate) volatiles using cryogenic methods. The warm manifold is used to process and purify volatiles that have been previously dried and therefore can operate at a lower temperature than that of the hot manifold.

The manifolds form a structure into which a number of gas path-ways are formed, and a number of gas processing valves, chemical processing reactors, pressure sensors, a cold finger and inter-connecting pipe connections are present for sample gas processing.

The reference gas system consists of a number of miniature pressure vessels that contain reference gases (ca. 10 bar). Flow control is provided by a number of miniature, high-performance, proportional flow valves that have low leak rates to minimise gas loss. In addition, a pressure sensor is used to measure the pressure of the reference gas. The use of

the variable volume bellows allows the gas pressure in the system to be controlled and matched with the pressure of the sample gas to allow precise isotopic measurements to be made.

4.4 Magnetic Sector System

The core sub-system of the MSS is the isotope ratio mass spectrometer which performs qualitative, quantitative and isotopic characterisation of reference and sample gases. In order to achieve accurate isotopic analysis (better than $\pm 1\%$) this will be a magnetic sector mass spectrometer that can operate in either of two modes: dynamic and static.

The baseline mass spectrometer of the MSS is a 6 cm radius, 90° magnetic sector with 5 Faraday cup detectors (3 positioned for C, N and O isotopic analysis and 2 positioned for H isotope analysis) and an electron multiplier detector. The MSS requires local electronics for the ion source and detectors. The mass spectrometer has a mass range, $m/z = 2$ to 150 amu and a mass resolution, $m/\Delta m$ of 65. The ion pump connected via a gate valve maintains a good vacuum in the mass spectrometer during dynamic analysis and evacuates sample after static analysis.

There are three dedicated sample inlets to the mass spectrometer: direct inlet, dynamic inlet and static inlet. The direct inlet, controlled by proportional flow valve, enables the mass spectrometer to analyse an aliquot of sample within the warm manifold. The dynamic inlet consists of the change-over valve connected to the reference side and sample side of the SPS by capillary tubing. In dynamic mode the mass spectrometer is continuously pumped whilst sample and reference gases from the SPS enter a change-over valve through capillary leaks which switches one of the gases into the mass spectrometer, thus allowing rapid sample/reference gas comparison. The rapid switching between sample and reference gases allows good isotopic precision ($\sim 0.1\%$) but requires μmol quantities of sample.

In static mode the mass spectrometer is sealed from the pumps and the entire sample enters the mass spectrometer for analysis. Following analysis (~ 15 minutes) the mass spectrometer is evacuated and the procedure repeated for the reference gas. Static analysis gives the greatest sensitivity ($\sim \text{nmol}$ sample size) at a cost of reduced isotope precision ($\sim \pm 1\%$). The ionization source can degrade reactive gases during the analysis so this technique is only suitable for gases such as noble gases, CO_2 , CO, N_2 and CH_4 .

During both static and dynamic analysis the gas pressure within the mass spectrometer is $\sim 10^{-7}$ mbar. Removal of the sample gas within the mass spectrometer is controlled by opening one or both gate valves - high throughput, high vacuum valves with a gas flow cross section area $> 1 \text{ cm}^2$ when open and a leak rate $< 10^{-5} \text{ mbar l s}^{-1}$ when closed. Pressures lower than 10^{-10} mbar can be obtained by opening the gate valve to vent, but allows lunar exosphere to enter the mass spectrometer giving a background signal. To remove this background the gate valve to vent is closed and the gate valve to the ion pump is opened. The ion pump has a pumping speed of 2 mbar l s^{-1} and requires a local 3 kV, current limited 1 mA voltage source.

The gate valve to vent allows another potential inlet to the magnetic sector. With the mass spectrometer evacuated the gate valve (when open) allows serendipitous direct analysis of ingressing molecular species and provide a redundant means of direct atmospheric analysis. In addition the operation of this mode at the same time as the AAS offers the possibility of cross calibration of the two techniques and/or investigation of geometric factors influencing the ingress of atmospheric species into the two detector systems.

4.5 L-VRAP Local Electronics System

At this stage the LES design is only at a conceptual level but it is based on that used in Ptolemy (Rosetta) such that L-VRAP operates as a stand-alone package. It is envisaged that functionality will be split across a number of printed circuit boards (PCBs), e.g. spacecraft interface, instrument control and gas-processing control. The conceptual design of the LES PCBs assumes the use of an electronics housing in aluminium alloy (~2 mm thick), which affords some protection against the expected levels of radiation.

The base-line design consists of a microcontroller together with its associated memory, an FPGA to contain the ESA HurriCANE core (if a CAN interface is not part of the micro) and an analogue to digital converter with associated multiplexers. The current baseline design uses a Leon3 part as this easily meets the mission requirements.

The electrical interface to the lander will use two 9-way standard D-type connectors, a male connector for the power supply and a socket for the CAN bus. The power supply connection will be routed to the main instrument supplies via an in-line EMC filter. It is expected that the interface will contain both a prime and redundant bus and the lander will indicate which bus to use by sending specific messages on the required bus. It is assumed that spacecraft time will be provided as a specific message type on the bus to allow L-VRAP to correctly time-stamp the outgoing house-keeping and science data telemetry.

Control of the SPS will require drive circuits for a number of discrete components e.g. valves, heaters, pressure sensors and piezo-electric actuators. The board will also contain an FPGA, ADC and DAC to produce and measure the analogue signals and minimise the interconnections between the LES cards as a serial link can be used to transfer the data to the microcontroller.

4.6 L-VRAP Structural & Thermal System

The STS provides overall structural basis for L-VRAP hardware, protection from dust and micrometeorites, a barrier against chemical contamination from the lander and environment (including residual fuel vented by the lander) and affords thermal control of overall instrument box.

The key challenges are heat-rejection during the lunar day and heat-conservation during the night. The base-line concept of the STS is a 1-2mm aluminium box (which also provides radiation shielding for the electronics) which is covered with 15 layers of MLI. The instrument base-plate is a CFRP-aluminium honeycomb-CFRP sandwich sheet which provides a stiff base-plate, good thermal isolation from the lander structure and also offers thermal isolation between L-VRAP sub-systems.

Initial thermal modelling indicates that a cooling radiator and associated baffling is required for daytime operations and to allow operation of the cold-finger. A thermally activated (passive) heat-switch is required to de-couple L-VRAP from the radiator during the lunar night to reduce heat losses.

Despite these precautions, during extended periods of darkness L-VRAP will cool from +40°C to - 55°C in 14 hours and will require 2.5 W of addition heater power to maintain a temperature about the electronics lower operational (survival) temperature either through conductive transfer to L-VRAP or via resistive “keep-alive” heaters.

5. L-VRAP resource requirements

The current mass breakdown is shown in Table 3 and are based on measured flight similar components (e.g. Ptolemy and Beagle2). Mass maturity margins have been applied according to the expectations of the Lunar Lander project team. The L-VRAP power and

energy budget is flexible and can be tailored to resource availability (effectively at any mission stage – from the design stage through to during actual on-surface operations phase). Average powers per experiment type are shown in Table 3. In all cases the maximum (peak) power would be limited to < 56 W.

For the purposes of this study, a baseline science operations scenario has been developed which fulfils the science requirements. The power, energy and data volume budgets have been derived for the baseline sequence, without a mobile payload element (MPE) (see Table 4). The duration columns show the duration during which L-VRAP will be operating, and as a % of the total duration of that mission phase. The values for the alternative mission scenario including the MPE are broadly similar.

6. Discussion

L-VRAP has been developed as a standalone instrument, however it needs to interact with the Lander and associated sub-systems and there are areas where a consideration of the whole Lander system can reduce resources and improve the science return.

6.1 Sampling

Possible limitation in the performance of the overall volatiles analysis protocol concerns the interface between the Lander's SSS and the SIS of L-VRAP. Open issues include difficulties in delivering the small solid samples required by L-VRAP, accurate determination of the mass (or volume) of the solid sample, and limitations in the ability to provide appropriate sub-samples (say, for instance, if the SSS was able to extract a core of some sort). The L-VRAP requires regolith samples to be delivered to the sample inlet port. In order to maximise scientific return, the sampling collection system needs to:

- collect from a wide range of targeted locations
- image the sample before and after collection
- deliver the sample to L-VRAP without the loss of volatiles
- deliver a representative sample of the regolith to L-VRAP
- minimise cross contamination between samples

Since the lander is likely to contaminate the surface, one of the important aims is to get a depth profile to at least 10cm of the volatiles. Contamination may also be avoided if the sampling mechanism can reach samples that may be protected from contamination such as beneath cobbles (64mm-256mm rocks). The proposed sampling mechanism (an arm with scoop) can meet these criteria, but by its very nature will deliver large (~g) samples to L-VRAP which will need to subdivide the sample before loading into the ovens, probably by having a tiltable plate mechanism on the inlet port, similar to GAP on Beagle2.

The inclusion of a Mobile Payload Element with a mole in the Lander payload would greatly increase the range of samples that could be acquired, possibly beyond the contamination zone. The operational plan would change, concentrating at more distant locations and also targeting areas that may be in continual darkness due to local topography. However the overall power budget remains unaffected as L-VRAP is limited to a total of 24 samples.

6.2 Electronics and Thermal

The electronics are located within the L-VRAP, however it may be necessary to split some of the individual component drivers so they are located adjacent to their respective devices. Since the reaction time is low (~1 second) then the local drivers can be addressed by I²C logic, hence reducing the amount of harnessing that is required. In addition the main electronics (processor and power converters) could be located inside the Lander thus

removing the necessity of the aluminium enclosure which is the major mass component (~1kg) of the Structural and Thermal System and replacing it with an MLI cage to satisfy the thermal requirements. However, local discrete drivers may need their own radiation shielding or be radiation hard components partially shielded by the devices they are driving which will reducing mass, but possibly increasing cost and complexity.

The electronics are also the determining factor in the thermal non-operational limits. Placing the electronics within the Lander and using electronics with a wider non-operational temperature range would reduce the overall non-operating temperature of L-VRAP so that it would require less power (if any) to remain above its survival temperature during non-illumination periods.

7. Conclusions

L-VRAP, the Lunar Volatiles and Resources Analysis Package, comprises two different types of mass spectrometer and associated gas processing hardware. Although the instrument itself is very capable its performance will nonetheless be constrained overall by any limitations in the selected sampling devices. Clearly there is scope to refine the objectives of the mission through a detailed appraisal of sampling/analysis considered as an end-to-end process.

L-VRAP is an instrument package that will determine the natural abundance and isotopic compositions of lunar polar volatiles and thus will gain an understanding of volatile sources and processes. Herein we describe an instrument concept that has been proposed to address the challenges of determining the nature and distribution of volatiles at the lunar surface (from perspectives that are notionally either scientific or resource oriented). The specifics of the design have been guided by the requirements of the proposed Lunar Lander mission. As such, the instrument is capable of a range of investigations, involving volatiles either from the regolith or from the exosphere. Because of the potentially limited reach of sampling devices on the Lunar Lander it has been necessary to consider how the effects of contamination imparted to the local surface during the descent could conspire to reduce the efficacy of the instrument. Our studies to date indicate that such concerns may be relatively easily overcome through the use of appropriate sampling techniques. But, regardless, characterisation of contamination at the landing site would be something that the instrument could address as well.

It is envisaged that L-VRAP, and its post-cursors, would become a standard part of any lunar exploration mission (including any that, in the future, would involve humans).

Acknowledgements

The work described herein was carried out under ESA contract 4000103345/11/NL/AF. We acknowledge support of our respective organisations in enabling the study to be undertaken. We feel the outcome has been an instrument concept of the highest levels of capability and sophistication; we are confident that this will fly in one form or another and we would be delighted to have the opportunity to become involved with building the actual hardware.

References

- Campbell D., Campbell B, Carter L.M., Margot J-L., and Stacy N.J.S., 2006. No evidence for thick deposits of ice at the lunar South Pole. *Nature*, 443, 835-837.
- Carpenter, J.D. et al., 2012. Paper in this issue. *Planet. Space Sci.* **XXX**, xxx-xxx.

- Colaprete, A., Schultz, P. and 15 others, 2010. Detection of water in the LCROSS ejecta plume. *Science*, **330**, 463-468.
- Epstein, S. and Taylor H.P. Jr., 1970. The concentration and isotopic composition of hydrogen, carbon and silicon in Apollo 11 lunar rocks and minerals. *Proc. Apollo 11 Lunar Sci. Conf.*, 1085-1096.
- Feldman, W.C., Maurice, S., Lawrence, D.J., Little, R.C., Lawson, S.L., Gasnault, O., Wiens, R.C., Barraclough, B.L., Elphic, R.C., Prettyman, T.H., Steinberg, J.T. and Binder, A.B. 2001. Evidence for water ice near the lunar poles. *J. Geophys. Res.*, **106**, E10, 23,231-13,152.
- Friedman, I., Gleason, J.D. and Hardcastle, K.G., 1970. Water, hydrogen, deuterium, carbon and C¹³ content of selected lunar material. *Proc. Apollo 11 Lunar Sci. Conf.*, 1103-1109.
- Gibson, E.K. Jr. and Johnson, S.M. 1971. Thermal analysis-inorganic gas release studies of lunar samples. *Proc. of the Second Lunar Sci. Conf.*, 1351-1366.
- Gibson E. K. Jr., Bustin R., and McKay D. S., 1988. Lunar Hydrogen: A resource for future use at lunar bases and space activities. In: *Lunar Bases & Space Activities in the 21st Century*, Paper LBS-88-158, 9 pages.
- Hayne, P.O., Greenhagen, B.T., Foote, M.C., Siegler, M.A., Vasavada, A.R. and Paige, D.A., 2010. Diviner lunar radiometer observations of the LCROSS impact. *Science*, **330**, 477-479.
- Kerr, R.A., 2010. How wet the Moon? Just damp enough to be interesting. *Science*, **330**, 434.
- Meslin, P.Y., Sabroux, J.C., Bassot, S. and Chassefiere, E., 2011. Experimental study of radon production and transport in an analogue for the Martian regolith. *Geochim. Cosmochim. Acta.*, **75**, 2256-2270.
- Mitrofanov, I.G., Sanin, A.B., Boynton, W.V. and 26 others, 2010. Hydrogen mapping of the lunar south pole using LRO neutron detector experiment LEND. *Science*, **330**, 483-486.
- Morse, A.D., Morgan, G.H., Andrews, D.J., Barber, S.J., Leese, M.R., Sheridan, S., Wright, I.P. and Pillinger, C.T., 2009. Ptolemy – A GCMS to measure the chemical and stable isotopic composition of a comet. In: *Rosetta – ESA's Mission to the Origin of the Solar System*, (eds. R.Schulz, C.Alexander, H.Boehnhardt and K.H.Glassmeier), Springer, ISBN 978-0-387-77517-3.
- Nozette, S., Lichtenburg C., Spudis P.D., Bonner R., Ort W., Malaret E., Robinson M.S., and Shoemaker E.M., 1996. The Clementine bistatic radar experiment. *Science*, **274**, 1495-1498.
- Paige, D.A., Siegler, M.A. and 25 others, 2010. Diviner lunar radiometer observations of cold traps in the moon's south polar region. *Science*, **330**, 479-482.
- Pieters, C.M., Goswami, J.N., Clark, R.N., Annadurai, M., Boardman, J., Buratti, B., Combe, J.P., Dyar, M.D., Green, R., Head, J.W., Hibbitts, C., Hicks, M., Isaacson, P., Kilma, R., Kramer, G., Kumar, S., Livo, E., Lundeen, S., Malaret, E., McCord, T., Mustard, J., Nettles, J., Petro, N., Runyon, C., Staid, M., Sunshine, J., Taylor, L.A., Tompkins, S. and Varanasi, P., 2009. Character and spatial distribution of OH/H₂O on the surface of the moon seen by M3 on Chandrayaan 1. *Science*, **87**, 568-572.
- Pillinger, C.T., et al., 2012. The role of the solar wind in the production of lunar volatiles. *Planet. Space Sci.* This issue.

- Richter, H.E., Yung, K.L., 2002. Development and testing of subsurface sampling devices for the Beagle 2 lander. *Planet. Space Sci.* **50**, 903–913
- Roberts, L., 1963. The Action of a Hypersonic Jet on a Dust Layer, Paper No 63-50. IAS.
- Schmitt, H.H., Kulcinski, G.L., Santarius, J.F., Ding, J., Malecki, M.J. and Zalewski, M.J., 2000. Solar wind hydrogen at the lunar poles. *Space 2000: 7th Int. Conf. and Exposition on Engineering, Construction, Operations and Business in Space*, Albuquerque, NM, 653-660.
- Simpson, R.A. and Tyler, G.L., 1999. Re-analysis of Clementine bistatic radar data from the lunar south pole. *J. Geophys. Res.*, **104**, E4, 3845-3862.
- Sims, M.R., Pillinger, C.T., Wright, I.P., and 26 authors, 1999. Beagle 2: a proposed exobiology lander for ESA's 2003 Mars Express Mission. *Adv. Space Res.*, **23**, 1925-1928.
- Stacey, N.J.S., Campbell, D.B. and Ford, P.G., 1997. Arecibo radar mapping of the lunar poles: a search for ice deposits. *Science*, **276**, 1527-1530.
- Todd, J.F.T., Barber, S.J., Wright, I.P., Morgan, G.H., Morse, A.D., Sheridan, S., Leese, M.R., Maynard, J., Evans, S.T., Pillinger, C.T., Drummond, D.L., Heys, S.C., Huq, E., Kent, B.J., Sawyer, E.C., Whalley, M.S. and Waltham, N.R., 2006. Ion trap mass spectrometry on a comet nucleus: the Ptolemy instrument and the Rosetta space mission. *J. Mass Spec.*, **42**, 1–10.
- Wright, I.P. and Pillinger, C.T., 1998. Modulus - an experiment to measure precise stable isotope ratios on cometary materials. *Adv. Space Res.*, **21**, 1537-1545.
- Wright, I.P., Sims, M.R. and Pillinger, C.T., 2003. Scientific objectives of the Beagle 2 lander. *Acta Astronautica*, **52**, 219-225.
- Wright, I.P., Barber, S.J., Morgan, G.H., Morse, A.D., Sheridan, S., Andrews, D.J., Yau, D., Evans, S.T., Leese, M.R., Zarnecki, J.C., Kent, B.J., Waltham, N.R., Whalley, M.S., Heys, S., Drummond, D.L., Edeson, R.L., Sawyer, E.C., Turner, R.F. and Pillinger, C.T., 2007. Ptolemy – an instrument to measure stable isotopic ratios of key volatiles on a cometary nucleus. *Space Sci. Rev.*, **128**, 363–381.
-

TABLE 1. List of L-VRAP requirements.

Number	Description
RQ1	<i>Volatiles and/or their volatile precursors shall be liberated from lunar regolith samples from known locations.</i>
RQ2	<i>L-VRAP shall determine the chemical identities of volatile species or, if relevant, their precursor(s) within the lunar regolith.</i>
RQ3	<i>L-VRAP shall provide a quantitative measure of the total volatile yield and the yields for individual volatiles as a function of the sample size. Where appropriate, it should quantify any precursor(s) within the regolith</i>
RQ4	<i>L-VRAP shall determine the isotopic abundance of the following element within volatile species as a differential measure relative to the accepted international standards with the following precisions: Hydrogen (δD) ± 100 ‰, Carbon ($\delta^{13}C$) ± 1 ‰, Nitrogen ($\delta^{15}N$) ± 10 ‰, Oxygen ($\delta^{18}O$) ± 0.1 ‰ and ($\delta^{17}O$) ± 1 ‰.</i>
RQ5	<i>L-VRAP shall determine the concentration by mass of $[H_2O + OH]$ in the top ~ 1 mm of regolith.</i>
RQ6	<i>L-VRAP shall determine the number density and composition of neutrals in the lunar exosphere at concentrations above $1 \text{ molecule cm}^{-3}$. L-VRAP should target the following neutrals in the lunar exosphere: H, He, Ne, Ar, Na, K, CH_4, H_2O, OH, CO_2, and NH_3.</i>
RQ7	<i>L-VRAP should determine the number density and composition of ions in the lunar exosphere at concentrations above 1 ion cm^{-3}. L-VRAP should target the following ions in the lunar exosphere: H^+, He^+, Ne^+, Ar^+, Na^+, K^+, CH_4^+, H_2O^+, OH^+, CO_2^+, and NH_3^+.</i>

Table 2. L-VRAP Mass Breakdown

Subsystem	Mass including margin (kg)
STS – Structural and Thermal System	1.2
LES – Local Electronics System	1.1
AAS – Atmospheric Analysis System	1.0
SIS – Solids Inlet System	0.7
SPS – Sample Processing System	1.5
MSS – Magnetic Sector System	2.5
Total including margin	8.0

Table 3. L-VRAP Power and Data Breakdown

Experiment	Average Power (W)	Duration (minutes)	Data Volume (kBytes)	
			Science	Housekeeping
Exosphere real time analysis	Medium (7.9)	611	242	306
Exosphere Passive Collection	Low (0.015)	659	63	30
Regolith “Quick” Analysis	Medium (8.0)	74	553	37
Regolith Detailed Analysis	Medium (9.3)	412	2258	206

Table 4. L-VRAP Operations Summary

Mission Phase	Duration	L-VRAP Operational Resources				
	(days)	Duration	(%)	Energy	Data vol.	Ovens
		(hours)		(Wh)	(kBytes)	(#)
Descent and Landing	0.042 (1 hour)	0	0.0	0.0	0	0
Lander Checkout	2	9.3	19.3	109.3	3247	0
Initial SS	30	199.6	27.8	1754.8	41947	17
Main SS	90	381.6	17.7	3166.0	26204	6
Extended SS	28	245.5	36.5	1991.1	9496	0
Total	150	836.0	23.2	7021.2	80894	23

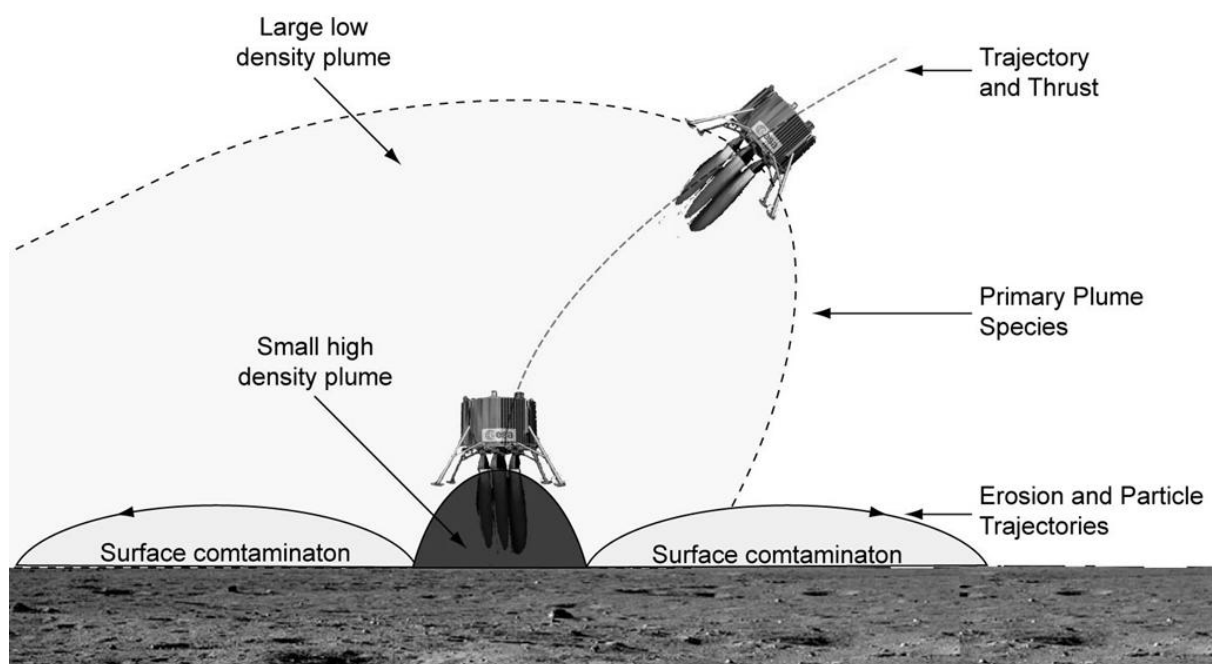


Figure 1. Problem breakdown: the issues surrounding contamination at the landing site

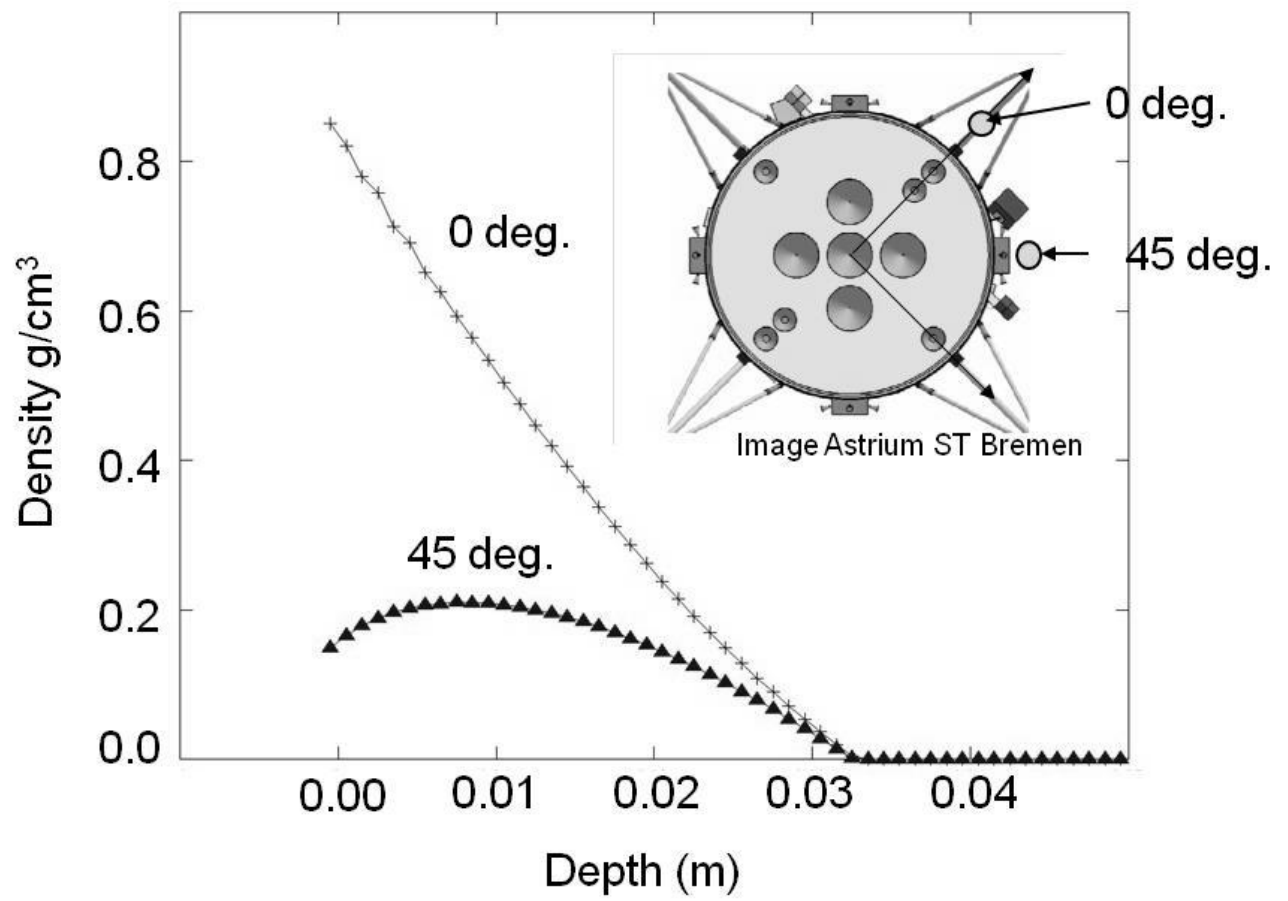


Figure 2. Erosion depth for present Lunar Lander along axis of approach

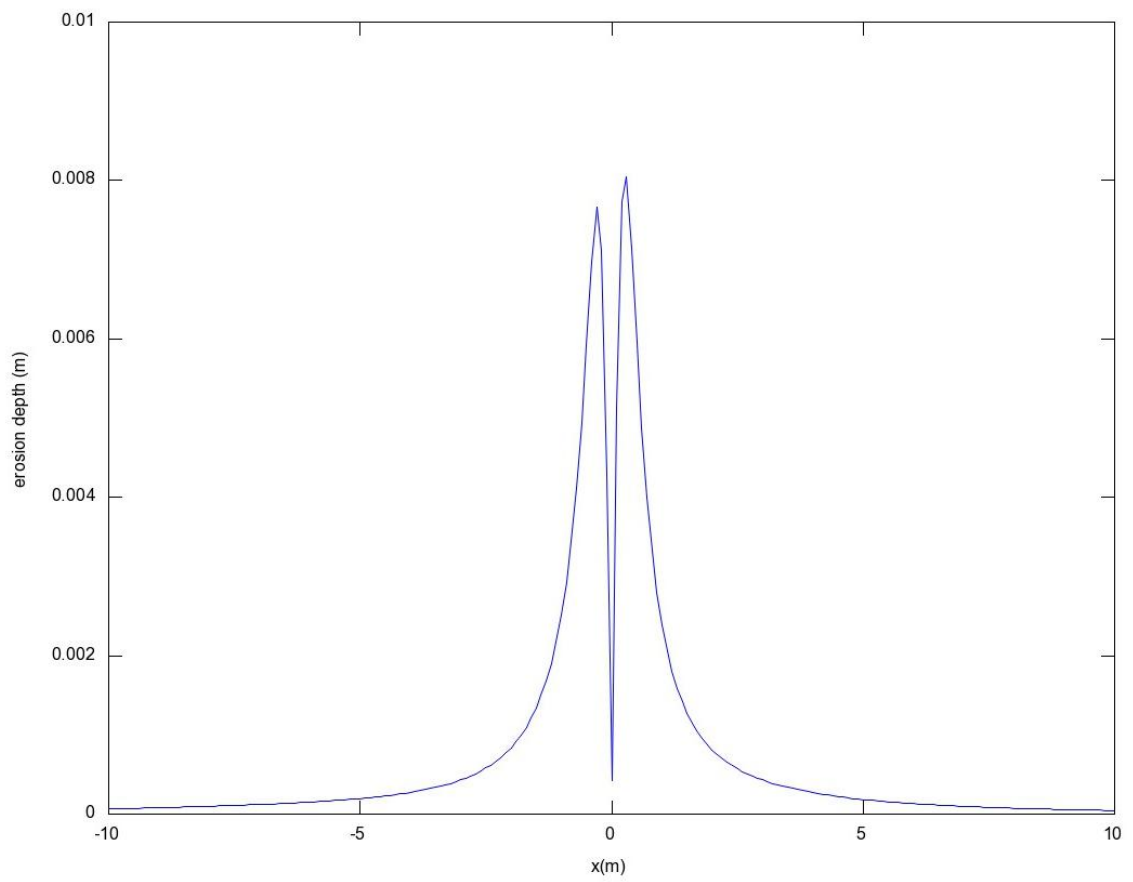


Figure 3. Erosion depth for present Lunar Lander along axis of approach

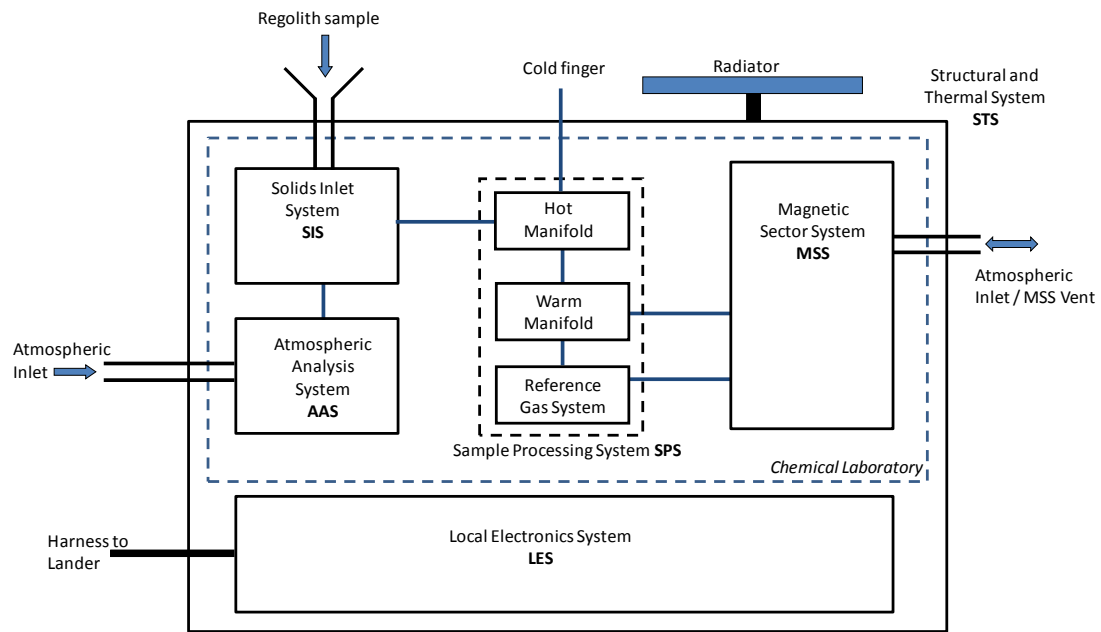


Figure 4. Schematic of L-VRAP

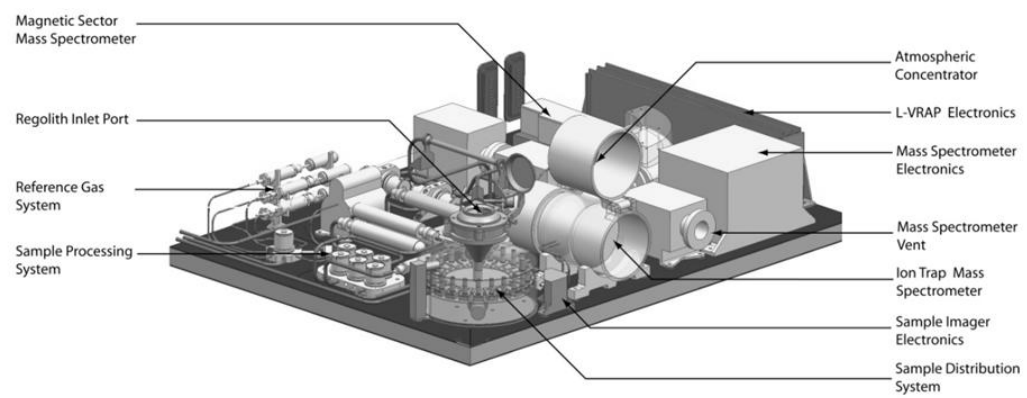


Figure 5. View from L-VRAP CAD model

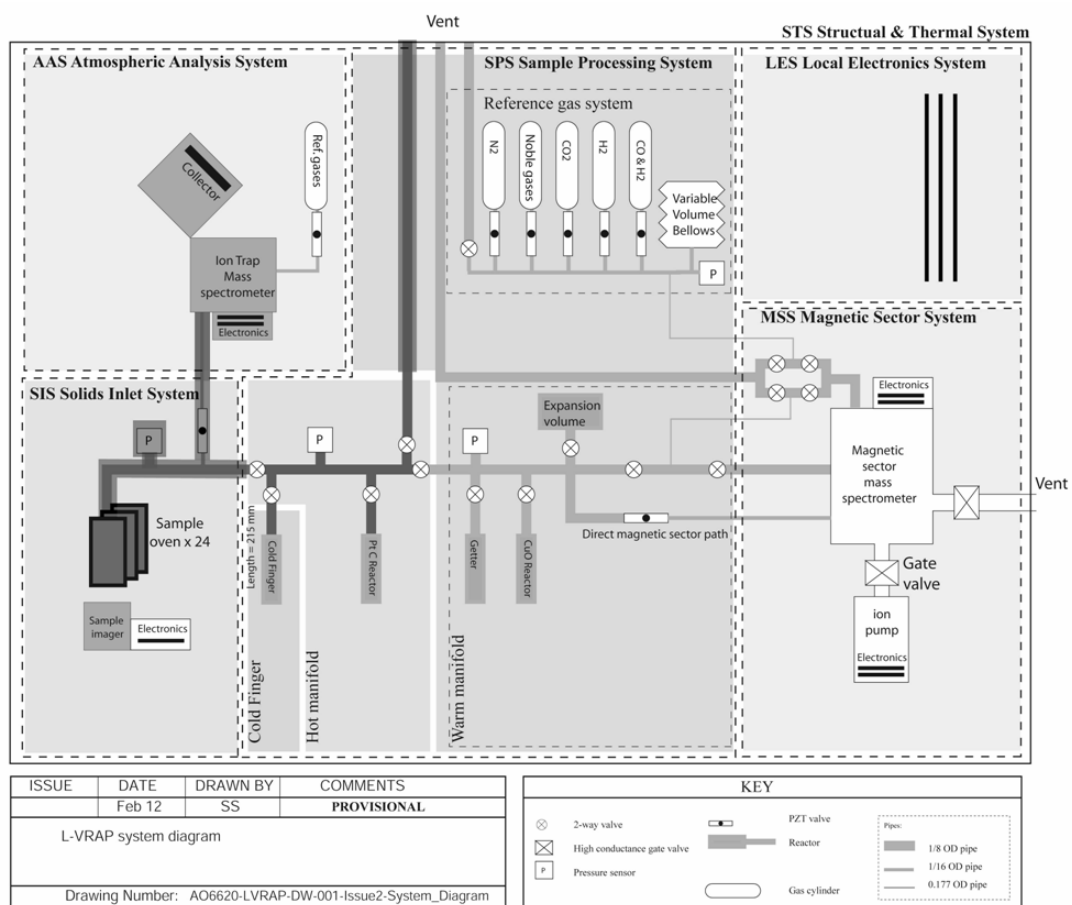


Figure 6. L-VRAP system diagram

